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Status Report

Groundwater Flow Modeling at the Rocky Flats Environmental Technology Site

• Environmental Restoration •
Rocky Flats Environmental Technology Site

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STATUS REPORT

GROUNDWATER FLOW MODELING AT THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

GOLDEN, COLORADO

Rocky Mountain Remediation Services, L.L.C.

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1.0 INTRODUCTION

This report presents a discussion on the status of a task to model the groundwater flow regime at the Rocky Flats Environmental Technology Site (RFETS) (the Site) in Golden, Colorado. The results presented here represent a continuing effort to model the groundwater system contained within the unconsolidated surficial materials at the RFETS. This modeling effort was performed to determining the effects of various remediation scenarios on groundwater flow at RFETS.

RFETS is located in northern Jefferson County in Colorado, approximately five miles south of Boulder and 16 miles northwest of downtown Denver. The Site consists of 6,550 acres of federally owned land of which 6,170 acres is a buffer zone surrounding an inner industrial complex. RFETS is a federal facility which began operation in 1951 to support nuclear weapons production and is owned by the Department of Energy, but operated by a private contractor.

A history of industrial activities related to the Site's mission have resulted in the contamination of the groundwater beneath the Site. Groundwater flow modeling has been undertaken at RFETS in order to understand the consequences of this contamination. The flow modeling presented here is intended to provide an overview of the near-surface flow system beneath the Site.

The goals of this modeling project are:

1. To aid in the hydrogeologic characterization of RFETS;
2. Provide basic information for estimating groundwater travel times;
3. Examine changes in the groundwater flow field from proposed Site closure activities; and
4. Achieve level 3 calibration.

The proposed methods by which a groundwater flow model of RFETS can address these goals are, respectively:

1. By providing a comprehensive picture of the groundwater flow regime at RFETS, the model will link the observational data from wells into a single interpretation that will consider such factors as hydraulic conductivity, bedrock topography, and groundwater recharge rates.
2. Groundwater travel times can be determined by using the mass flux rates computed by the model.
3. As envisioned, a fully implemented groundwater model will include mass transfer to and from surface water bodies, allowing groundwater/surface-water interactions to be investigated.
4. In addition to providing estimates of recharge to the groundwater system, the mass flux rates computed by the model can be used to determine the volumes of water flowing through different areas at RFETS.
5. Model can predict the change in groundwater flow system due to capping various areas on the Site.

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Site. This discussion provides the general hydrogeologic conceptual model on which the implementation of the flow model is based. A brief discussion of the computer code used for the sitewide flow modeling is given in Section 3.0. Section 4.0 discusses the actual implementation of the flow modeling computer code for use at the Site. The status of the calibration for the flow modeling and a discussion of additional refinements required for improving the model are given in Sections 5.0 and 6.0, respectively.

2.0 CONCEPTUAL HYDROGEOLOGIC MODEL

2.1 GEOLOGY

RFETS is located four miles east of the Front Range section of the Southern Rocky Mountain province, along the western margin of the Colorado Piedmont section of the Great Plains physiographic province (Spencer, 1961). RFETS is on a pediment that dips approximately one degree to the east, and is dissected by several easterly flowing, ephemeral streams, that either originate on plant site, or one to two miles to the west.

The geology of the area around RFETS consists of several surficial deposits overlying sedimentary bedrock layers. The surficial deposits are made up of pediment alluvium, colluvium, valley-fill alluvium, and artificial fill that unconformably overlie the bedrock formations. These near-surface alluvial deposits range from Quaternary to Pleistocene in age. The bedrock consists of several sedimentary formations with a regional dip of approximately two degrees to the east, ranging from Pennsylvanian/Permian to Cretaceous in age. The subcropping strata become progressively older from east to west. West of the Site, the sedimentary strata are exposed along the western limb of a monoclinal fold. The dip increases to the west as the layers abut against Precambrian-aged crystalline rocks (EG&G, 1991). The total thickness of the geologic section for the Paleozoic- and the Mesozoic-aged strata is approximately 13,000 feet.

The uppermost hydrostratigraphic unit at RFETS exists as an unconfined water-bearing unit. This upper water-bearing unit is primarily contained within the unconsolidated alluvial materials and includes the Rocky Flats Alluvium, colluvium, and the valley-fill alluvium. Additionally, shallow, subcropping bedrock sandstones and the upper weathered bedrock are included in the conceptual definition of the uppermost hydrostratigraphic unit at RFETS.

The Rocky Flats Alluvium is a gravelly, alluvial-fan deposit consisting of poorly sorted, angular to rounded, coarse-grained gravels, sands, and clays with thickness of as much as 100 feet. The colluvium predominantly consist of a thin deposit of silty clay and clayey silt, with some gravel and sand, and is produced by mass wasting along valley slopes. The valley-fill deposits are represented by well to poorly sorted, reworked materials of Rocky Flats Alluvium, colluvium, and weathered bedrock. These deposits are found in the base of drainage's throughout the area. Both the colluvium and the valley-fill alluvium range in thickness from less than one foot to several tens of feet.

2.1.1 Rocky Flats Alluvium

The Rocky Flats Alluvium is a Quaternary-aged pediment gravel deposited as a laterally coalescing alluvial-fan deposit derived from Coal Creek Canyon. The deposit thins from west to east, with thickness ranging from one to approximately 100 feet. In the central portion of RFETS, the deposit is approximately 15 to 25 feet thick. It was deposited across a gently sloping erosional surface cut into the underlying bedrock. The slope of the pediment near its apex is approximately 1.5 degrees to the east (EG&G, 1992b).

The Rocky Flats Alluvium consists of poorly to moderately sorted, poorly stratified clays, silts, sands, gravel's, and cobbles. In some areas the Alluvium has developed a significant near-surface caliche layer. The Rocky Flats Alluvium varies in color, ranging from light to dusky brown, dark yellowish orange, grayish orange, to dark gray (EG&G, 1991). Subsequent dissection and headward erosion by creeks in the area have cut through the alluvium into the underlying bedrock, exposing the base of the alluvium along some valley walls.

2.1.2 Colluvium

Colluvial deposits consist of surface soil, displaced Rocky Flats Alluvium, and slump deposits resulting from mass wasting along valley slopes. These deposits vary in thickness from less than one foot to approximately 30 feet. The colluvium is predominantly silty clay and clayey silt with some gravel and sand.

2.1.3 Valley-Fill Alluvium

The valley-fill alluvial deposits, present in the bottoms of modern stream drainages, are composed of linear deposits of cobbles, gravel, and sands. These deposits are typically less than ten feet thick. Usually these deposits contain more sand than the Rocky Flats Alluvium and are better sorted.

2.2 CLIMATE

The area of Colorado in which RFETS is located exhibits a semi-arid climate and receives an average of approximately 15 inches of precipitation annually (EG&G, 1992a). On the average, daily summer maximum temperatures at the Site range from 55 to 85 degrees Fahrenheit (°F) and winter maximum temperatures range from 90° to 45° F. Approximately 50 percent of the precipitation is received from snowfall during the winter and spring. Summer thunderstorms account for approximately 30 percent of the precipitation, with the remainder being received as light rain and snow during the fall. Approximately 85 inches of snow are deposited annually. Computed potential evapotranspiration is estimated to be approximately 39 inches per year (Fedors and Warner, 1993) .

2.3 GROUNDWATER HYDROLOGY

2.3.1 General

The primary source of groundwater within the unconsolidated surficial materials at RFETS is the infiltration of precipitation, either from direct rainfall or snowmelt. Other sources include recharge from streams, ditches, and ponds, as well as some subsurface flow from upgradient recharge areas. Groundwater flows predominately in a west-to-east direction, following the general bedrock and topographic gradients. The highest groundwater elevations (and greatest saturated thickness) typically occur in the spring, with the lowest elevations occurring in the fall and winter. Losses from the surficial groundwater system include discharge to surface water through streams and seeps, evapotranspiration, and recharge to underlying bedrock. Subsurface groundwater discharge to off-site areas is believed to take place primarily as underflow along the major drainages.

The uppermost unconfined aquifer at RFETS consists primarily of unconsolidated alluvial material. These alluvial materials include the Rocky Flats Alluvium, which forms a high, gently sloping plateau across the Site; colluvium located along valley slopes; and valley fill alluvium present in the modern stream drainages. In the western part of RFETS, where the thickness of the Rocky Flats Alluvium reaches 90 feet, the depth to the water table is 50 to 70 feet below the surface. In general, the depth to the water table becomes shallower from west to east as the alluvial material thins. Seeps are common along valley slopes at the base of the Rocky Flats Alluvium where it is in contact with claystones of the Arapahoe/Laramie Formations. During dry portions of the year, extensive areas of the alluvial materials may become unsaturated. The location and extent of these areas varies over time.

2.3.2 Groundwater Flow

A contour map of water level elevation was constructed using data from wells within the unconsolidated surficial materials, collected during the time period from April 1, 1992 to May 30, 1994 (see Figure 2-1). Variations in the screened interval and depth of penetration of the wells may introduce some variation between the observed and actual groundwater elevations. This time interval is used here to represent conditions during spring 1994 and was selected based on its apparent representativeness of typical water level conditions at the Site.

Generally, groundwater in the Rocky Flats Alluvium flows laterally along the top of the claystone bedrock surface. It moves in an easterly direction in areas upgradient of RFETS, and in a semi-radial pattern to the north, east, and south. Typically, the underlying claystones have a low hydraulic conductivity, on the order of 1 x 10^{-7} centimeters per second (cm/s) (EG&G, 1992c, Table 1). This low hydraulic conductivity limits the amount of vertical flux from the surficial materials into the bedrock and effectively constrains the flow in the overlying surficial materials to a primarily lateral course. There is significant evidence that bedrock topography controls groundwater flow within the alluvial materials. This control is particularly important in areas with a thin saturated thickness.

Groundwater flow in colluvium is characterized by relatively steep horizontal gradients toward stream drainages, and a highly variable saturated thickness controlled by bedrock topography and proximity to recharge sources (i.e., subsurface discharge from the Rocky Flats Alluvium). Flow through the colluvium provides subsurface recharge to the valley-fill alluvium. Groundwater within the valley-fill alluvium flows parallel to the main stream drainage. The groundwater and surface water systems within the valley-fill alluvium are closely related and may exchange mass in either direction at various locations along the drainage (Fedors and Warner, 1993).

Water level differences between bedrock and alluvial wells indicate a large downward vertical hydraulic gradient. This large gradient is an indication of hydraulic disconnection. However, if the alluvium and bedrock units were in complete hydraulic connection, the amount of vertical flow through the bedrock claystones would be small based on the fine-grained lithology and the limited occurrence of fractures at depth observed in cores. Fracturing, where evident, is most abundant in the weathered bedrock zone. Cores from borings indicate that fractures occur individually and in discrete zones, and that they are generally oblique to near vertical. In addition, some fractures exhibit mineralized areas (i.e., iron staining) in the upper portion of the bedrock, appear to heal with increased depth (EG&G, 1992d). Recent work by RMRS on the vertical migration potential of contaminants in the claystone bedrock has confirmed these conclusions.

2.3.3 Anthropogenic Effects

The introduction of manmade surface and subsurface water flow control features has resulted in a noticeable impact to the Site groundwater flow regime. These features typically result in increased or decreased groundwater elevations near structures. Structures affecting the largest areas within the RFETS groundwater flow system are the groundwater interception and diversion system at the existing Site landfill, the solar evaporation ponds groundwater interceptor trench system, the 881 Hillside french drain system, and the footing drains associated with the subsurface portions of many of the buildings within the industrial complex.

The groundwater intercepter trench system for the solar evaporation ponds collects groundwater from the unconsolidated surficial materials on the slope between the solar evaporation ponds and Walnut Creek. The effect of this is a de-saturated area on the slope north-east of the solar ponds (see Figure 2-1).

The 881 Hillside french drain system is designed to intercept all subsurface water in the unconsolidated surficial materials which flow down the hill slope towards Woman Creek. This system was completed in April 1992 and appears to be somewhat effective in de-saturating the undissolved materials in this location. Although they are of a smaller scale to the drainage systems discussed above, building footing drains may have a notable impact on groundwater elevations due to the concentration of buildings in the industrial area at RFETS.

Although not a large-scale impact on the groundwater flow system, sampling events may cause apparent effects by temporarily lowering the water level in wells that have a long recovery time. The hydrograph for well 7087 shows this effect (Figure 2-2). Some of the low water level measurements are the result of measuring water level while the well is recovering from a sampling event. Several of the water sampling events are followed by a series of lowered water level measurements that define a exponential curve, similar to a well recovery curve. This indicates that the well was still in the process of recovering from the sampling event when subsequent water-level measurements were made. This slow recharge may explain some of the erratic water level fluctuations shown by some wells.

2.4 SURFACE WATER HYDROLOGY

The surface water system at RFETS is interconnected with the groundwater system. Surface water recharge to the Rocky Flats Alluvium, valley fill alluvium, and colluvium occurs as seepage from streams, ditches, and ponds. Conversely, groundwater is discharged as surface water along streams and at localized seeps where groundwater reaches the land surface. These seeps typically occur along valley slopes near the Rocky Flats Alluvium/claystone contact.

Four streams flow through RFETS: North Walnut Creek, South Walnut Creek, Woman Creek, and Rock Creek. All of these streams drain the Site and are considered to be ephemeral. North Walnut Creek and South Walnut Creek converge to become Walnut Creek, which flows toward Great Western Reservoir. A diversion canal, operated by the city of Broomfield, diverts flow from Walnut Creek around the reservoir. Woman Creek originates west of the Site and drains the south part of the site. Its natural drainage is to the east, towards Standley Lake. However, a diversion structure (Mower Ditch), located within the Site boundaries, diverts much of the flow from Woman Creek into Mower Reservoir. The Rock Creek drainage is located in the north part of the Site. It flows to the northeast, eventually joining Coal Creek beyond the northern boundary of the Site. In addition to the natural drainages, nine ditches convey water through the Site area. Except where conveyed by aqueducts, all of these ditches are unlined and tend to lose water through seepage into the underlying subsurface materials.

Within the natural drainages, a series of detention ponds has been constructed within the natural drainages to control the release of plant discharges and to collect surface runoff. Ponds located along North Walnut Creek are designated A-l through A-5, and ponds located along South Walnut Creek are designated B-l through B-5. Ponds A-l, A-2, B-l, and B-2 are reserved for spill control and are isolated from drainage waters flowing down Walnut Creek. Pond B-3 receives treated effluent from the Sanitary Waste Treatment Plant. The remaining A and B series ponds receive runoff from the plant's storm sewer system. Pond C-l is a flow-through reservoir located along Woman Creek. Pond C-2 is isolated from Woman Creek and is used to collect diverted surface flow from the South Interceptor Ditch along the north slope of the Woman Creek drainage. Other surface water features at RFETS include a detention pond located at the existing landfill, and ponds D-1 and D-2 that are part of a diversion canal located near the southeast corner of RFETS.

3.0 MATHEMATICAL MODEL

This section discusses general aspects of the computer code used for the sitewide flow modeling, why this code was selected, and the output generated by the code. The computer code selected for the sitewide flow modeling project was the modular, three-dimensional, finite-difference groundwater flow model of the U.S. Geological Survey (USGS) commonly referred to as MODFLOW (McDonald and Harbaugh, 1988). Below is a discussion of the criteria used in selecting MODFLOW for this project. The main criteria used for selecting the computer code to use for this project were that the selected model should:

1. Incorporate key hydrogeologic processes and accurately represent conditions known to occur at the Site.
2. Satisfy the objectives of the study.
3. Be verified using published equations and solutions.
4. Be complete and well documented and preferably available in the public domain.
5. Be practical and cost effective in terms of actual applications as well as resolution of uncertainty.

The MODFLOW model was selected based on each of the above criteria based on the following observations:

1. MODFLOW is a modular program with a wide variety of packages available for simulating different hydrogeologic processes. The key hydrogeologic processes at RFETS (areal recharge, groundwater/surface water interactions, two-dimensional flow in saturated porous media) are all simulated within various MODFLOW model packages.

2. The main objective of this project was to provide a saturated flow model that encompasses the main plant and buffer zone areas of RFETS for use in analyzing ASAP scenarios. MODFLOW meets the main objective by providing a two-dimensional simulation of groundwater flow for a gridwork of points covering the area of interest. The use of MODFLOW will also allow meeting the future objective because there are models that can use the flow field output from MODFLOW to do particle tracking (Pollock, 1989) and/or fate and transport simulations (Zheng, 1992).

3. MODFLOW is a widely used finite-difference flow model that has gained broad acceptance and recognition (Anderson and Woessner, 1992; van der Heijde et al., 1988).

4. MODFLOW is a complete package for modeling two-dimensional flow through layered porous media; no additional code is required for the flow computations. The MODFLOW model is documented in a comprehensive USGS publication (McDonald and Harbaugh, 1988), and the source code is available in the public domain.

5. MODFLOW is a modular, three-dimensional, finite-difference saturated-flow model written in FORTRAN. Several modeling pre-processors and post-processors are available for aiding in MODFLOW input data development and output analysis. The MODFLOW model is widely available and is written in standard FORTRAN 77. It can easily be implemented on any computer that has a FORTRAN 77 compiler. These factors provide for the practical and cost effective application of MODFLOW to the sitewide modeling project. The structure and character of the MODFLOW input and output data sets provide sufficient means for standard sensitivity analysis.

Although capable of simulating vertical flow, MODFLOW is commonly used to simulate two-dimensional layered systems with varying vertical conductance between the layers. Vertical and horizontal model dimensions are defined by the thickness of the layers and the row and column spacing, respectively. The model grid is implemented in a block-centered fashion.

The sitewide flow simulations use the standard required MODFLOW modules for basic model input (subroutine BAS1) and conductance term calculation (subroutine BCF1) (McDonald and Harbaugh, 1988). The strictly impartial procedure solver (subroutine SIP) was used to solve the matrix of equations generated by the finite-difference approximations. The optional output control module was also used to provide better control of the format and frequency of the output generated by the model.

In addition to the modules discussed above, the recharge package (subroutine RCH1AL) (McDonald and Harbaugh, 1988) and streamflow routing package (subroutine STRIRP) (Prudic, 1989) were used in the sitewide flow modeling. The recharge package was included because areal recharge through precipitation is an important factor in groundwater flow at RFETS. Inclusion of the streamflow routing package was done to incorporate groundwater/surface-water interactions into the model.

4.0 MODEL IMPLEMENTATION

4.1 INTRODUCTION

This chapter discusses the implementation of the groundwater flow simulation code selected for use in RFETS sitewide flow model. The implementation of the simulation code involves developing input data for the code that reflect the hydrogeologic conditions at the Site. This chapter also discusses the manner in which the MODFLOW model was transferred to and executed on the computer systems within RMRS.

4.2 INSTALLATION AND PREPARATION OF MODFLOW MODEL

The primary source code for the MODFLOW model was obtained from the International Ground Water Modeling Center (IGWMC) located at the Colorado School of Mines in Golden, Colorado. The IGWMC is an internationally recognized organization, which acts as a distributor of groundwater-related models and model information. The source code for the streamflow routing package (subroutine STRIRP)

(Prudic, 1989) was obtained from the USGS. The FORTRAN source code files were transferred to an Silicon Graphics Indigo 2 UNIX workstation for compilation.

After the MODFLOW source code was installed and compiled, several example problems were executed. The output from these sample problems was verified against the documentation provided with the sample problems. The output from all the sample problems tested matched the documented output within the expected tolerances (see McDonald and Harbaugh, 1988, pg. D-5). These results were taken as evidence that the MODFLOW computer code was correctly implemented and operating as expected on the SGI work stations.

4.3 IMPLEMENTATION OF THE CONCEPTUAL HYDROGEOLOGIC MODEL

The conceptual hydrogeologic model is emulated by the computer flow model by designating input parameters appropriate for the site. The current version of the sitewide flow model focuses on the waters in the unconsolidated surficial materials. It treats the Rocky Flats Alluvium, hill slope colluvium, and valley fill materials as a single, unconfined layer within the MODFLOW model. The modeling presented here represents conditions during the spring of 1994.

4.3.1 Model Domain

4.3.1.1 Spatial Domain

The model covers an areal extent which includes all of RFETS' industrial area and a large portion of the RFETS buffer zone (Figure 4-1). The extent of the model grid nodes in State Plane coordinates is from 744500 to 755100 feet northing and from 2076500 to 2094050 feet easting. The grid is oriented with the rows aligned along an east-west direction. This orientation aligns the model grid so that the grid rows are parallel with the predominant groundwater flow direction. The grid is currently implemented with a node spacing ranging from 50 to 200 feet along rows and columns. The model grid contains 151 columns and 98 rows.

4.3.1.2 Time Domain

The simulations included in this status report focus on the spring 1994 time period. This period was chosen because it is relatively recent, and because the spring of 1994 appeared to be representative of average or typical water level conditions at the Site. The model was considered steady state and spring 1994 water levels typical for the Site.

4.3.2 Processes Modeled

Some of the factors affecting groundwater flow at the Site are not incorporated within the subsurface flow system itself. These factors are external processes which have a direct influence on the groundwater flow system. The two most significant external processes included in the sitewide flow model are areal recharge and loss and gain to surface streams. These two factors have an important influence on the head elevations at RFETS and so influence the subsequent flow pattern.

4.3.2.1 Recharge From Precipitation

Percolation of meteoric waters through the unsaturated zone to the water table can account for significant recharge to the subsurface flow system. There are several factors that influence this process. The primary factor that can restrict the amount of infiltrating water available to recharge the groundwater system at the Site is loss to evapotranspiration. The process of evapotranspiration may remove water held in the unsaturated zone before it has an opportunity to recharge the saturated zone. The potential evapotranspiration at RFETS has been calculated to be approximately 39 inches of water per year (Fedors and Warner, 1993). This value is approximately twice the annual precipitation rate at RFETS. This demonstrates the large potential for water loss through evapotranspiration.

Although MODFLOW includes a module to model water loss through evapotranspiration, a much simpler and commonly used approach is to look at the net recharge to the groundwater system. By using the idea of net recharge, one does not have to be concerned with the actual evapotranspiration values, but only with estimating the amount of water remaining to recharge the groundwater system. In MODFLOW this can be done using the recharge package, which adds an areally distributed recharge value (feet/day per unit area) into the flow calculations. The values of net recharge used in the sitewide flow model are discussed in Section 4.3.3.2.

4.3.2.2 Surface Water Recharge and Discharge

The network of surface drainage's that cross the Site can transfer water to and from the groundwater system. Initial studies of Woman Creek by Fedors and Warner (1993) indicate that it varies from effluent to influent along its various segments, and that the character of an individual segment may change through time. This transfer of water volume between the surface and subsurface flow systems was simulated in RFETS sitewide flow model using the MODFLOW stream routing package.

The stream routing package compares the head in the stream with the head in the aquifer and computes the direction (to or from the stream) and magnitude (based on the conductance of the stream bed) of water flux. The primary drainages at the Site (Woman, Walnut, and Rock Creek), as well as additional drainages at the Site, were included in the model. The only man-made canal currently included in the model is Mower Ditch, which is used to divert water from Woman Creek to Mower Reservoir (Section 2.3.4). This was included because a large portion of the flow in Woman Creek is continually diverted into this ditch. The other irrigation ditches that cross RFETS were not included because they are only used sporadically. Specific details regarding input to the stream routing package are discussed in Section 4.3.3.3.

Groundwater recharge from ponds within the Woman and Walnut Creek drainages is included in the model using constant head cells. All of the A series ponds (with the exception of A-5), B series ponds, C series ponds, and the landfill pond are modeled in this manner. The A-5 pond is not currently included because of its small size. Pond D-1 is located in a portion of the model with inactive grid nodes, and Pond D-2 is located outside of the area covered by the model.

4.3.2.3 Subsurface Drains

Most of the major manmade subsurface water flow control features discussed in Section 2.3.3 have been included in this version of the sitewide flow model. This includes the present landfill, solar evaporation ponds, 881 Hillside subsurface drain systems, and the building footing drains in the Industrial Area. These features were included in the current model to realistically portray the effect of these features on the groundwater flow system. Drain elevations, where below or at the top of bedrock, were set to 0.1 feet above bedrock to avoid numerical errors stemming from calculated water levels being at or below the bottom of the model.

4.3.3 Model Parameters

This section reviews the values or range of values of input parameters used for the sitewide flow modeling at the Site. Where available, RFETS field measured values were used as a basis for the input values. Appropriate literature values were used as guidance when field data were unavailable or had significant uncertainty. Some parameters had neither field data nor appropriate literature values. In this case professional judgment was used in determining the input value. The input data files for MODFLOW were set up to use length units of feet and time units of days. These were the most convenient and applicable units for this project. All the data in the following discussion are presented in these units.

4.3.3.1 Hydraulic Conductivity

Hydraulic conductivity is a parameter that enters directly into the flux calculations within MODFLOW. Field and laboratory measured values of hydraulic conductivity are available for the unconsolidated surficial materials at the Site. A summary of hydraulic conductivity information is listed in Table 4.1 (a more comprehensive database can be found in the Hydrogeological Characterization Report). As shown by this listing, there is a considerable range in the values of hydraulic conductivity determined for specific material types. Some of this variability is associated with differing test conditions and some reflects the heterogeneity of the geologic materials.

Table 4.1
Summary of Observed Values of Hydraulic Conductivity (ft./day)

	Minimum	Maximum	Geometric Mean
Rocky Flats Alluvium	8.2E-05	1.4E+02	4.4E-01
Hill Slope Colluvium	1.2E-02	6.2E+01	7.2E-01
Valley Fill Alluvium	6.0E-03	1.1E+02	4.0E+00

Table 4.2 provides a summary of the hydraulic conductivity values currently being used in RFETS sitewide flow model. A comparison of the values used in the flow model against the observed data (Figure 4-2) verifies that the hydraulic conductivity values used in the model are within the range of the observed data.

In determining the initial spatial distribution of hydraulic conductivity values, the model grid was divided into separate regions based on the surficial geologic material. These regions were defined as areas covered by Rocky Flats Alluvium, hill slope colluvium, or valley fill alluvium. The initial values of hydraulic conductivity for each region were based on the geometric mean of the observed data for that material type. This distribution was then adjusted during the model calibration process. In the model, hydraulic conductivity is considered isotropic in the north-south and east-west directions. The initial distribution of hydraulic conductivities in the model is based on the previous sitewide model (EG&G, 1993b).

Table 4.2
Summary of Values of Hydraulic Conductivity (ft/day) Used in Model

	Minimum	Maximum	Initial Values
Rocky Flats Alluvium	5.0E-02	1.2E+00	4.4E-01
Hill Slope Colluvium	1.OE-01	3.0E+00	7.2E-01
Valley Fill Alluvium	2.0E+00	1. 1e+011.	1e+01/7.6E-01

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4.3.3.2 Areal Recharge

As discussed in section 4.3.2.1, the sitewide flow model uses a net recharge approach in incorporating recharge from precipitation. The process of obtaining estimates of recharge is problematic (Anderson and Woessner, 1992). Initial estimates of areal recharge were based on examples from previous modeling projects at RFETS (Fedors and Warner, 1993, EG&G, 1993). The spatial distribution of these values was based on the general distribution of the different surficial materials. This was done in a fashion similar to that used for hydraulic conductivity (Section 4.3.2.1). Information from the Soil Conservation Service Soil Survey for the Golden Area (U.S.D.A., 1980) was also used as a guide for the relative infiltration rates of the different surficial materials. Values of net recharge used in the model ranged from 0 to 9.0E-04 ft./day. A value of zero was used for the highly developed areas of RFETS. A typical value for areas composed of Rocky Flats Alluvium was 4.5E-04 ft./day. Areas of hill slope colluvium would typically have a value of 8.5E-05 ft./day, with valley-fill areas having values ranging between 2.0E-04 to 5.0E-04 ft./day.

4.3.3.3 Stream Data

The input requirements to the MODFLOW stream routing package, as used here, and how these requirements were met are listed in Table 4.3.

Table 4.3 Stream Routing Data

Input Data Required	Value Used in Model
Inflow at upstream end of stream	Assumed to be zero
Stream stage	Assumed to be 0.5 feet
Hydraulic conductance of the streambed	Computed using the hydraulic conductivity,stream length, width, stage, and streambed bottom elevation.
Elevation of the top of the streambed	Topographic elevation
Elevation of the bottom of the streambed	Topographic elevation minus three feet or bedrock elevation if alluvium is less than three feet thick.
Width of the stream channel*	Assumed to be three feet
Slope of the stream channel*	Assumed to be 0.020
Manning's roughness coefficient (n)*	Assumed to be 0.035

*used to compute stream stage

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The last three parameters in Table 4.3 are used to compute the approximate stream stage. The other parameters are used in the calculation of the volumetric water flux to or from the underlying aquifer.

The water inflow from upstream stream segments not explicitly modeled were considered to be zero. This is physically correct for many streams. Those streams that may have some contribution from upstream flow were set at zero until reliable stream flow data are obtained. The stream stage listed in Table 4.3 is primarily used to compute the conductance of the streambed (McDonald and Harbaugh, 1988, pg. 6-10) and the listed value was chosen as being representative. Because the inflows to all stream segments are zero, the initial stream stage actually used in the model is equal to the elevation of the top of the streambed (Prudic, 1988, pg. 10). The hydraulic conductivity used to compute the streambed conductance is the same conductivity discussed in Section 4.3.2.1. The stream length is the straight line distance of the stream trace across an individual MODFLOW grid cell, which was computed using digitized stream maps. The value of Manning's roughness coefficient was chosen based on communications with RFETS Surface Water Division and values listed in Prudic (1988). The remaining values in Table 4.3 were used as listed.

4.3.3.4 Base of Model (Bedrock Elevation)

Because the current flow model only considers the unconsolidated surficial materials, the base of the model was set at the top of bedrock. Information for the top of bedrock elevation is incorporated into the flow model as a two-dimensional grid of values; one value for each grid node. The grid of bedrock elevations was produced using the Dynamic Graphics Incorporated (DGI) surface- interpolation software. The original grid was developed using a 50-foot grid spacing. This data was then re-sampled at the variable grid spacing used in the flow model. The data used to develop this grid comes from a compilation of 1167 data points for bedrock elevation assembled from borehole information. The technique used for creating the original bedrock surface grid is described in EG&G (1993b). This gridded surface was erected using 734 data points. Subsequently collected data (from borings and wells) were used to update the bedrock surface grid.

4.3.3.5 Initial Water Table Elevation

As a starting point for the simulations, an initial groundwater elevation (head) grid is input to the MODFLOW model. For RFETS sitewide simulations, this grid was developed to represent conditions during the spring of 1994 (see Section 4.3.1.2). A contour map of this grid is presented in Figure 2-1.

The groundwater elevation grid represents average groundwater elevations in alluvial materials for the period between April 1 and May 30, 1994. The data to create this grid were retrieved from the Rocky Flats Environmental Data System (RFEDS) and includes information from 347 wells, 108 of which were considered to be dry. A well was considered to be in a saturated area if a valid water level measurement was indicated for a majority of the time period (i.e., not indicated as dry in RFEDS). If the data or the recorded water level was below the top of bedrock, the well was considered dry.

Several grid editing iterations were performed involving the bedrock elevation and topographic elevated grids. As an aid in the development of the initial-head grid, a saturated thickness grid was also developed. The saturated-thickness grid was produced by subtracting the bedrock-elevation grid from the groundwater elevation grid. Further refinements in the saturatedthickness grid were made by manually adjusting the isopach lines and recreating the grid to reflect the new contour configuration. Following this the new saturatedthickness grid was added to the bedrock-elevation grid to recreate the groundwater elevation grid. This process was repeated several times to obtain a satisfactory set of groundwater elevation and saturatedthickness grids. Both the groundwater elevation and saturated- thickness grids were produced using the DGI surface-interpolation software. The original grids were developed using a 50-foot grid spacing. The data were then re-sampled at the grid spacings used in the flow model.

4.3.3.6 Model Boundary Conditions

As part of the mathematical definition of the flow model, the conditions at the outer boundary of the model grid must be specified. In MODFLOW these boundary conditions are typically either no-flow or constant head. No-flow boundaries are composed of grid cells that are not active in the flow system. Because these cells are not incorporated into the flow system, there is no water flux into or out of this type of cell. Constant head boundaries are composed of grid cells for which the head does not change during the entire simulation. Both of these types of boundaries were used for the sitewide flow modeling.

The western and eastern grid margins of the flow model were setup as constant head boundaries (Figure 4-1). This was done primarily because there was no well-defined physical flow boundary near these margins. The north and south grid margins were composed of a mixture of no-flow and constant head boundaries. No-flow boundaries were used where a groundwater flow divide was believed to exist; elsewhere, constant head cells were employed.

The outer boundaries of the model were located at such a distance from the main Site industrial complex that the influence of boundary conditions should be minimal. This is particularly true for the north and south boundaries, which have major drainages between themselves and the main RFETS complex.

5.0 MODEL CALIBRATION

This chapter describes the current calibration status of the sitewide groundwater flow model. This includes a description of the goals of the calibration, factors limiting the calibration, the techniques used during calibration, and the results of the calibration. Model calibration is the process of adjusting the model input parameters to minimize the difference between the model output and some

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sets of observed data. In the case of RFETS sitewide flow model, the model calibration parameters are the hydraulic conductivity and recharge values, and the observed data are water level elevations measured in wells during the spring of 1992.

5.1 CALIBRATION GOAL

In a general sense, the goal of the calibration process is to reduce the difference between the modeled and observed groundwater elevations. More specifically, it is typical to define some criteria to judge the calibration. Several evaluation criteria were used in assessing RFETS sitewide flow model calibration.

5.1.1 Calibration Data Set

Of the 347 wells used to develop the initial-head grid (Section 4.3.3.5), 108 were dropped from the calibration because they were dry. The remaining 239 wells were used as observation data in the calibration process. Dry wells were used in an attempt to duplicate de-saturated areas within the model.

5.1.2 Sources of Error

When comparing modeled and observed data, a certain portion of the error is associated with the observed data themselves. The error associated with the observation data is primarily due to the discrete nature of the model domain. Anderson and Woessner (1992) attribute this error to three sources: 1) Transient effects; 2) scaling effects; and 3) interpolation errors.

Transient effects are errors associated with averaging observed heads across some time period. For the sitewide model, this is introduced by using observed heads that represent an average of the period from April 1, 1994 to May 30, 1994. Many of the wells would be expected to have some water level fluctuation during this time period which would not be represented by the model.

Scaling effects are errors introduced by heterogeneities within the subsurface materials that are at a scale smaller than an individual model grid cell. For example, small volumes of high or low conductivity materials located at an observation well may have a significant influence on water levels in the well, but could not be explicitly included in the flow model. Altering the flow model to fit what may be a nonrepresentative water level caused by a small-scale heterogeneity is inappropriate because the model is meant to represent average conditions within a given grid cell.

Because calibration data points rarely fall at the center of a grid cell, there is some interpolation error involved in comparing modeled and observed heads. For the sitewide flow modeling, a measure of this error can be expressed by comparing the grid of initial heads for the model to the observed data. The values of interpolation error for the observation data set used here, ranged from 5.0 to 4.9 feet. The mean and standard deviation were -0.7 and 1.0 feet, respectively. The absolute value of interpolation errors for the observation wells ranged from 0.002 to 5.0 feet; the average of the absolute values was 0.5 feet.

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5.1.3 Calibration Goals

To evaluate when the model is close enough to the observed data to be considered calibrated, a set of calibration goals is defined. These calibration goals should be set in accordance with the uncertainty contained in the observation data (Section 5.1.2). For the RFETS sitewide flow model, the largest source of comparison error related to the observation data is that from the data point interpolation. Considering this, the calibration goals were set relative to the interpolation error discussed in Section 5.1.2. and map error standards. Three calibration levels were set, and level 3 was the lowest calibration level.

The National Map Accuracy Standards (NMAS) deal with horizontal and vertical accuracy for USGS basemaps. Vertical accuracy standards state that no more than 10 percent of the test (observation) points must be within one-half of the contour interval. Adaptation of the vertical accuracy standards gives guidance for the selection of validation targets. Since the grids were edited based on a 20-foot contour interval, 90% of the observation points must be within the -10 to +10 feet error range.

As a first pass calibration check, a series of calibration levels were set and the number of observation points expected to exceed this level of calibration were determined (Table 5.1).

Table 5.1 Calibration Levels

Level	Basis for Level	Calibration Value Range (ft)	% of Observation Points Expected to Exceed this Calibration Value	Number of Observation Points Expected to Exceed this Value
1	Mean$\pm$ 1	-1 to 1	32	77
2	Mean $\pm$ 2	-2 to 2	5	12
3	Mean $\pm$ 1/2 C.I.	-10 to 10	10	24

Each row in Table 5.1 represents a calibration level (Anderson and Woessner, 1992, pg. 244), against which the calibration observation data points were tested. The basis for each level is listed in the second column. The calibration value range represents the range of acceptable calibration errors for that level. These were computed using a mean of zero and a standard deviation of three feet. A mean calibration error of zero was used because this is the expected value if the errors do not show a positive or negative bias. The third column in this table represents the percentage of calibration points expected to exceed that level, assuming the interpolation errors follow a normal distribution. The fourth column in Table 5.1 is the number of calibration points expected to exceed that level using a data set of 239 calibration points.

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The calibration levels in Table 5.1 provide a general feel for the model calibration errors relative to the overall distribution of the interpolation errors. To evaluate individual observation points, the calibration error from each point can be compared to its interpolation error. Because the interpolation error is error inherent in the specification of the model domain, the model could be considered calibrated when the model calibration errors are less than or equal to the interpolation errors at each observation point. For this report, a calibration point was considered calibrated if the calibration error was within two feet of the interpolation error value. For example, a calibration point with an interpolation error of one foot was considered within calibration criteria if the model calibration was less than or equal to three feet. Two feet was considered the smallest absolute calibration error to be expected at this scale. At the coarsest level of calibration (level 3), the model would be considered calibrated if the calibration error was within 10 feet of the original data point.

The RFETS sitewide flow model included the MODFLOW stream routing package to incorporate groundwater/surface-water interactions. This package provides estimates of stream discharge along individual reaches of the stream. The comparison of computed and observed stream discharge could be used as an additional calibration criteria. Because a comparison of this type requires estimates of flow contributions from surface runoff, only a general comparison of stream discharges was made for this report. Comparisons were also made using estimated drain effluent flows, The sitewide mode included the MODFLOW drain package. Where values were available, comparisons could be made between the estimated values of drain effluent and the simulated drain flows. Table 5.2 presents estimated drain effluent values for several subsurface drains on the Site.

TABLE 5.2
Estimated Drain Effluent Values

Subsurface Drain	Estimated Value (gallons/yr.)
881 Hillside french drain	237,250
Interceptor trench system	1,788,500
Building 444	73250
Building 881	1.1×10^{-6}
Building 875/886	164,601
Building 865*	394,857

*Value based on one-time springtime measurements.

5.2 CALIBRATION PROCESS

During the calibration process, various model parameters are adjusted so that the model output (values of head) more closely match the observed data. This is typically an iterative process that involves running the model, evaluating the output, adjusting the input, and running the model again. This was the technique used for this project. The model output was evaluated against the observation data and against the general pattern of head and head change (drawdown) values. In areas with significant calibration errors, the model inputs were adjusted. The hydraulic conductivity and net recharge values were the model inputs changed during model calibration. One or both of these parameters were adjusted depending on the magnitude of the calibration error and the hydrogeologic setting of the area. Typically during the calibration process, hydraulic conductivity was the first parameter adjusted. In areas where the modeled heads were too high, the conductivity values were increased; in areas where the modeled heads were too low, conductivity values were decreased. If adjustments of the hydraulic conductivity values within the expected ranges (see Table 4.1) were not adequate to improve the calibration, then the values of areal recharge were adjusted. Recharge values were increased to increase the modeled heads, or decreased to decrease the modeled head elevations. Because the streambed conductance parameter for the stream routing package is influenced by the hydraulic conductivity (Section 4.3.3.3), these terms were recalculated whenever hydraulic conductivity values were altered.

5.3 CURRENT CALIBRATION STATUS

The results presented here reflect the current status of the model calibration. The model currently meets level 3 calibration. Because of the location of the remediation measures and the relative density of observation wells, more emphasis was placed on calibrating those areas in and surrounding the RFETS industrial area than on the peripheral regions of RFETS. MODFLOW computes a volumetric budget to monitor total mass balance during a simulation to determine whether significant mass balance errors are accumulating. The volumetric budget for the sitewide flow model showed a mass balance error (calculated as mass in minus mass out) of -4.5% over the entire simulation. Mass balance errors on the order of 1% are typically considered tolerable (Anderson and Woessner, 1992, pg. 223).

Comparison of simulated and observed water level contours indicate that the flow model tends to smooth out some of the small-scale irregularities in the map of observation data (Figure 5-1). Some of this smoothing is due to the coarseness of the grid used in the flow model. Additionally, areas along the north and south no-flow boundaries. Some of the minor drainages (and along the eastern boundary) show some head discrepancies. It is impossible to determine the significance of these discrepancies in areas that lack observation wells.

Some locations near the RFETS industrial area that show notable calibration errors are minor areas within the Industrial Area, in the eastern half of Operable Unit 2, and in the area northeast of the Industrial Area. These discrepancies indicate additional calibration of hydraulic conductivity and recharge parameters are needed in those regions.

Calibration level 3 was achieved with a majority of calibration error falling between -10 and +10 feet. In many areas, especially the Industrial Area, level 2 calibration was achieved. The mean calibration error is 7.7 feet with a standard deviation of 13.1 feet.

6.0 SUMMARY AND FUTURE WORK

The sitewide flow model is being developed to help in the general characterization of the hydrologic system at the Site and to assist investigations and remedial design for Site closure activities, such as plume containment/remediation. The development and current status of the flow model have been discussed in previous chapters of this report. Some observations and insights regarding the flow model, along with suggestions for improving the model are given below.

Figure 5-2 presents the current calibration map for the groundwater flow error model. Green areas are within the ±10 foot calibration error criteria, while red areas are outside this range. It should be noted that much of the red areas do not contain calibration points and may reflect differences in the grids rather than differences between observed and simulated water levels.

6.1 OBSERVATIONS

A primary observation regarding this project is that the general pattern of modeled heads matches head contours developed from observation data fairly well within level 3 calibration standards. Additionally, the model is able to produce this relatively realistic head distribution using hydraulic conductivity values within the range of those observed at the Site (Figure 4-2) as well as realistic values of recharge. Drain effluents were not used for calibration at these levels.

6.2 IMPROVEMENTS

The calibration results and discussion presented in this status report suggest several areas of improvement. These are presented according to priority and grouped according to whether they are necessary or suggested improvements. Currently the modeled obtains a converged solution, but more work is needed to refine the calibration. The areas in the model that require improvement are:

- Areas east and northeast of the Industrial Area
- Areas east of Operable Unit 2
- Eastern boundary
- Minor areas in the Industrial Area

6.2.1 Necessary Improvements

These improvements are considered necessary to improve confidence in the flow model. These should be seen as a continuation of the work presented in this status report. As discussed in Section 5.3, additional improvements in the model calibration are possible and necessary. This will involve a continuation of the calibration process as presented in Section 5.2. This process will be concentrated at those areas with a large calibration error relative to their interpolation error, as these locations show the greatest prospect for improvement in the model calibration. The eastern

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half of Operable Unit 2 may warrant a separate model due to the hydrogeologic complexities of this area. The current scale of the sitewide model is probably not sufficient to simulate these complexities. It may be possible to simulate this area with the Operable Unit 2 Corrective Measures Study/Feasibility Study model (EG&G, 1995).

6.2.2 Modeling Scenarios

Once the model is calibrated, various Site closure scenarios may be examined. The input for the flow model will be adjusted to simulate:

- Proposed cap installations
- Proposed upgradient diversions
- Proposed remedial installations

Furthermore, partial trenching (using a MODFLOW add-on such as DKTH3D) will be completed to examine long-term effectiveness of site closure remediation measures.

7.0 SUMMARY

In general, the version of the sitewide flow model presented in this report, is capable of generating water table elevations which match those from observation wells and has achieved the goal of level 3 calibration. This model should not be considered completely calibrated. Some specific areas for improvement in the model head calibration have been identified (Section 5.3), and will need to be addressed to refine this work. Although stream-aquifer interactions have been included in the model, stream flow data from the model is not currently used as a calibration criteria. Comparison of modeled streamflow and field measured values may be possible as additional data become available. Although the model provides a water table elevation distribution that matches the pattern, additional calibration improvements must be performed before the model is used for Site closure assessments.

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GROUNDWATER FLOW MODELING AT THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

FIGURES